The NASA ASP Air Quality Applied Sciences Team (AQAST): A Retrospective

by Daniel J. Jacob (Harvard), Tracey Holloway (U. Wisconsin), Bryan N. Duncan (NASA/GSFC), Jana Milford (U. Colorado), Daniel Knight (U. Colorado). Patrick Dolwick (USEPA), Thomas Moore (WRAP)

submitted to the NASA Applied Sciences Program
February 2016

Contents

1. Introduction

In 2010, the NASA Applied Sciences Program (ASP) solicited proposals to form an Air Quality Applied Sciences Team (AQAST) through the Research Opportunities in Space and Earth Sciences (ROSES) omnibus solicitation. AQAST was to "*focus on specific applied research topics and demonstrations required to advance the air quality management community's use and application of Earth science observations and models in decision making*." The solicitation was to support a self-organizing team of 12-15 members for five years with a budget of $3.5M per year. Five years later, we report on the self-organization of AQAST, successes and challenges, performance metrics, highlights, the AQAST legacy, and what lessons can be drawn for future ASP Science Teams.

AQAST responded to a need to increase the value of Earth science products for US air quality management (AQM). The AQM community is defined here as the staff at federal, regional, state, and local AQ agencies responsible for the design and implementation of air pollution control policies. A particular motivation for AQAST was to promote awareness, appreciation, and use of satellite data by this community.

The AQAST solicitation included a number of innovative approaches. First was the concept of a Science Team associated with a general application theme, rather than a targeted mission or product. Second was the freedom for AQAST to self-organize and develop its own rules of engagement with the AQM community. Most AQAST PIs received base funding to allow them to respond nimbly to the evolving needs of the AQM community. AQAST also had access to supplemental funds for PIs to pool their expertise in "Tiger Teams" designed to address pressing AQM needs. AQAST was tasked to engage with the broadest suite of air quality agencies, from national to local. Organizing and managing the team under this broad mandate involved a number of elements reviewed in this report.

2. Solicitation and team selection

2.1 Solicitation

AQAST was solicited as "A.32 Air Quality Applied Sciences Team" as part of ROSES 2010. It was intended to be the prototype of an envisioned suite of Applied Sciences teams to address various applications of Earth science. As such, it was to serve as a testbed for how these teams would function. Here we present a few important excerpts from the solicitation that guided the purpose and organization of AQAST.

[ASP] is initiating Applied Sciences teams to focus on key applications-oriented challenges and critical data products needed by the applied community and end users. The teams will address topical sets of applied topics that require a sustained, coordinated, and targeted applied research investment and will identify specific data products and provide applications- oriented feedback to Earth science research.

The structure of the Air Quality Applied Sciences team is expected to include members broadly representative of the air quality community…

The Air Quality Applied Sciences Team will be conducting new, focused applied science activities on emerging and urgent needs in the air quality community. As such, the members of the team will be funded at a baseline level, with additional funds available each year for priority tasks identified by the Air Quality Applied Sciences Team and approved by the Air Quality Program Manager.

The Team will be self organizing …, and, on an annual basis, create a prioritized list of additional activities to address needs within the air quality community that the Team is qualified to address. The intent here is to provide for more rapid, short-term action on emerging needs than is possible through the systematic Air Quality Applied Sciences solicitations, as well as to provide sustained and coordinated efforts to advance systematic use of NASA Earth science products in the air quality community. Upon approval by the Air Quality Applied Sciences Program Manager, the "tiger team" activities will access additional funding each year for members of the team.

The proposals should enable the use of research knowledge, modeling capabilities, data products, visualizations, etc. in air quality management, policy analysis, decision making, actions, impact assessments, and evaluation activities.

Because of the novel nature of this applied sciences team, care should be taken to document all investigators' qualifications for membership. Proposals should identify and substantiate the specific expertise of the proposer and the proposer's engagement with the air quality community. Proposals should identify a particular issue in air quality and outline an approach to address this issue as an indication of the proposer's capability to assess air quality needs and formulate solutions.

2.2 Team selection

Nineteen AQAST PIs were selected through the solicitation and are listed in Table 1. Three were selected without base funding but were eligible for funding through Tiger Teams. Twelve of the PIs were from universities, one from NASA, one from EPA, two from NOAA, and three from other national labs. Regional/global modeling and satellite data analysis were well represented in the expertise of the selected team. Some areas described in the scope of the solicitation were not represented, in particular policy and economic analysis.

Daniel Jacob was appointed as AQAST leader by the ASP management. In December 2012, Jacob appointed PI Tracey Holloway from U. Wisconsin as AQAST deputy leader with approval from ASP management. Appointment of a deputy leader was not planned in the solicitation but turned out to be very helpful, with Holloway taking on particular responsibility for communications and outreach. Having the deputy leader be a PI from a different institution than the leader also provided some desirable decentralization in AQAST leadership.

2.3 Recommendations from selection panel and ASP leadership

The ASP leadership and the review panel that selected AQAST offered several general recommendations for the organization and operation of the Team:

1. **AQAST should have a broad scope in working with Earth science data and models, and not be limited to satellite data or to NASA products.** This broad mandate was helpful in the early phase of AQAST by dispelling the perception among AQ managers that since AQAST was funded by NASA it would be all about satellites. Engaging AQ managers at the level of regional/global modeling and suborbital data, with which they had familiarity and confidence, helped to develop initial relationships.

2. **Priority should be on the needs of US air quality management. AQAST should not expand its mandate to air quality in other countries.** This was important in keeping AQAST nationally relevant and avoiding dilution of its focus. It would have been all too tempting for AQAST members to focus on air pollution problems in East Asia, but this would not have engaged the US AQM community.

3. **AQAST should engage not just with federal AQ agencies but also with agencies at the state/local level.** This was particularly useful guidance. It would have been natural for AQAST to focus its interactions with EPA and NOAA at the level of the national labs, where there is a high level of scientific expertise with which AQAST members could readily relate. But engaging state and local agencies turned out to be of considerable importance because they were in greatest need for support from AQAST and had some very interesting problems to solve.

4. **AQAST should focus on early successes to receive recognition and interest from the AQM community.** Indeed, AQMs invited at our first AQAST meeting (May 2011) were openly skeptical of the value of AQAST and satellite data. They had their hands full with operational requirements and had no time to work with us. We had to turn this attitude around fast, and it was important to reach for low-hanging fruit and vigorously advertise early successes. This led us to develop effective communication channels with the AQM community through the semiannual AQAST meetings, regular newsletters, a professional website, and an on-line media center for public releases.

5. **AQAST should focus on serving AQM needs through services other than scientific publications.** This was important in reminding the Team that the success of AQAST would be determined by its service to the AQM community, not publications. There was indeed a perception from the AQM community that AQAST scientists would just be chasing publications and not follow through on delivering products that AQ managers could actually use. We had to dispel that perception. At the same time, devaluating scientific publications as an AQAST outcome would not have been wise. First, AQ managers often need the backing of peer-reviewed scientific publications to motivate regulatory actions. Second, most AQAST PIs were university scientists (some on tenure track) for whom the standard of promotion and recognition is scientific publication. A balance between publications and other forms of service had to be struck. Fortunately, the AQAST PIs understood that publications and service are not mutually exclusive, on the contrary – service increases the impact of publications and provides ideas for new

publications. Service can also be a powerful motivator for graduate students, who are generally enthusiastic to see their research used for societal benefit.

3. Self-organization of AQAST and engagement with AQM community

3.1 Investigator projects, Tiger Teams, leadership

The AQAST funding model described in the ROSES solicitation included (1) baseline funding to individual PIs, (2) Tiger Teams, (3) team leadership. We review here these different elements.

Investigator Projects (IPs). Most PIs received $150K/year in base funding. The solicitation provided no specific requirements for the use of this base funding. It was intended for the PI to conduct self-defined projects that would flexibly respond to the evolving needs of the AQM community, and would serve this community in a way that best fit the PI's areas of expertise. We referred to the projects conducted with this baseline funding as Investigator Projects (IPs).

While respecting the PI's independence, we defined three requirements for their IPs: (1) they had to involve Earth science data and tools that the AQM community does not commonly use, (2) they had to involve one or more named AQM partners, (3) they had to define 1-year outcomes and deliverables. PIs were required to submit yearly 1-page descriptions of their planned IPs for review by the AQAST leadership and the broader team. These "1-pagers" had to follow a specific format including names of AQM partners, description of problem to be solved and approach to be followed, deliverables, and expected AQM outcome. The projects were listed on the AQAST website with links to the 1-pagers.

Tiger Teams (TTs). The AQAST funding model included additional funds accessible by the PIs for "Tiger Teams" that would pool the expertise of several PIs to address a pressing AQM problem. The total funding made available by ASP for AQAST TTs was arranged by fiscal year and was uncertain from year to year. It was $1.5M for FY2012, $0.9M for FY2013, $1.0M for each of FY2014 and FY2015, and none for FY2016. Guidance from ASP management was that (1) TT funds should remain within the AQAST community (they could not be used to engage external investigators except under exceptional circumstances), (2) all AQAST PIs should be TT members for at least part of the 5-year AQAST tenure, and (3) the TTs should be internally competed in an informal way.

TTs provided an extremely valuable resource to (1) have AQAST PIs work as a team, (2) design competed projects that would best serve the AQM community, (3) generate discussion on AQM priorities. We experimented with different approaches for selecting TTs, to balance the conflicting goals of collaboration within the team and internal competition. Reliance on AQAST PIs as reviewers was problematic for team spirit, for several reasons: (1) there was conflict between collaboration and competition; (2) competition for the small pool of funds could lead to gaming of the system; (3) losers could become disengaged from the team. On the other hand, we found that engaging the AQM community in the review process was very effective. It ensured that AQM priorities were reflected in the review process, and it provided an avenue for the AQM community to set AQAST directions. We also had to strike a balance between nimbleness and continuity in TTs. It was important to have the resources to form new TTs every year, while at

the same time recognizing that projects often take longer than a year to produce the desired returns.

By Year 3 we settled on the following multi-step approach for selecting TTs:

1. AQAST PIs submitted their TT ideas as powerpoint "1-sliders", with no mention of who would be involved as AQAST participants or AQM partners. 15 project ideas were thus submitted in year 3.
2. The set of 15 slides was posted on the web and a poll was sent to an extensive AQM mailing list asking respondents to rate the proposals by priority and to write in any additional ideas. We received 62 poll responses from the AQM community and the consensus in these responses was that the 15 projects indeed addressed the highest AQM priorities. On the basis of the priority ratings from the AQM community, 7 project ideas were selected for further competition.
3. 2-page TT proposals were then submitted by the TT PIs for each of the project ideas, following a format similar to the IP 1-pagers (including identification of the team members, AQM partners, outcomes, deliverables). The proposals were then reviewed and rated anonymously by the AQAST PIs and by a panel of AQM representatives who helped us over the years with TT selections: Pat Dolwick of EPA, Tom Moore of WRAP, Susan Wierman of MARAMA, and Paul Miller of NESCAUM.
4. On the basis of these reviews (and requiring a mean ranking of "very good" or better), 6 of the TT proposals were selected for funding. This left some AQAST PIs without a TT involvement; we gave them the option to join a selected TT by describing what they would contribute and submitting the request to the TT PI for approval. At the end of this process all AQAST PIs were engaged in at least one TT.
5. We then distributed all the TT funds evenly among the AQAST PIs, with up to a factor of 2 more for TT PIs depending on the size of their TTs.

The above approach had the merit of producing TTs that were vetted by the AQM community, engaged all AQAST PIs in a team spirit, and got the AQM community more involved with the selection of AQAST projects. In Year 4 we re-opened the process, but (and this is hardly surprising) the consensus among AQAST PIs was that the Year 3 TTs were very successful and should be allowed to continue. We asked for 2-page renewal proposals for these TTs, including summaries of accomplishments, and also had one new TT proposal. We repeated Steps 3-5 above and were able to select the new TT project as well as continue funding the Year 3 TTs.

Team leadership and communications. AQAST funding included $150K for a team leader (Jacob) to coordinate, prioritize, and advertise team activities. Jacob appointed Holloway in Year 2 to serve as deputy leader and some of the leadership funds were re-routed to U. Wisconsin to support her role. Team leadership involved a range of tasks in (1) organizing and representing the team, (2) selecting TTs, (3) identifying AQM priorities for the team to work on, and (4) developing and maintaining communication vehicles.

3.2 AQAST communication vehicles

Developing effective two-way communication vehicles with the AQM community was critical for AQAST's success. Major communication vehicles developed by AQAST included (1) semi-

annual AQAST meetings with strong participation from the AQM community, (2) additional meetings and workshops held in partnership with the AQM community, (3) an AQAST website (http://www.aqast.org/) hosted at Harvard, (4) an AQAST media center (http://www.aqast-media.org/) managed by U. Wisconsin, (5) quarterly to semiannual newsletters, (6) a Twitter account (@NASA_AQAST), and (7) AQM feedback via ARSET. We describe here these different vehicles.

Semi-annual meetings. A semi-annual schedule of team meetings was chosen to provide a balance between effectively reaching out to the geographically dispersed AQM community while avoiding meeting fatigue. A central objective of AQAST meetings was to engage the AQM community in (1) learning about AQAST activities and accomplishments, (2) building relationships with AQAST members and spinning up new AQAST projects, and (3) educating AQAST members as to their major challenges and priorities. The meetings were stand-alone, not associated with any other meeting. Juxtaposing AQAST meetings with AQM community meetings was initially considered in order to facilitate participation, but we decided that this would dilute the energy of AQAST meetings and distract from their impact.

A focus of AQAST was to reach out to local, state, and regional AQ agencies. These agencies have limited or non-existent travel budgets. Therefore, AQAST meetings were held in different locations around the US (Figure 1) to increase the opportunities for agencies to attend. Our initial plan was to co-organize meetings with AQ agencies as a way to promote their engagement, but we soon found out that (except for very large agencies like EPA and CARB) the agencies were ill-equipped to organize meetings and/or would require AQAST to contribute meeting funds that we did not have. Instead we asked university PIs to organize meetings at their institutions. This worked very well and had a number of advantages: (1) the PIs had access to well-equipped and free meeting facilities, had supporting staff and students for meeting logistics, and could often contribute catering with internal funds; (2) the meetings could attract the local community of students, postdocs, and scientists outside AQAST; (3) AQM community participants enjoyed the opportunity to escape their usual environment and meet in the relaxed setting of a university campus; (4) there were no security requirements hindering participation; (5) the hosting PI acquired visibility with local agencies to forge future partnerships. The only problem with this mode of operations is that it limited us geographically, since we had no university PI west of Colorado. We addressed the problem by organizing a meeting at the California Air Resources Board.

AQAST meetings lasted 2.5 days, with the last half-day reserved for internal AQAST matters and TT breakouts. The first 2 days featured 15-minute presentations by AQAST scientists, other application scientists, AQ managers, as well as posters and other activities. At least half a day was dedicated to AQ managers' sessions, featuring presentations by AQ managers followed by discussion panels to identify pressing needs and how AQAST could address them. These needs were then reviewed in the internal AQAST session at the end of each meeting to assess how well we were responding to them and what more should be done. Over the course of AQAST's tenure the AQ managers' sessions grew in importance to occupy most of one day.

Other meetings and workshops. AQAST members organized, co-organized, and otherwise contributed to a number of topical meetings in partnership with the AQM community. Prominent examples included:

- The 2015 Energy Summit (U. Wisconsin, Oct 2015) organized by Tracey Holloway and that brought together a number of AQ managers and AQAST PIs.
- The Transboundary Ozone Pollution in the Western US Conference (Yosemite, Mar-Apr 2015) co-sponsored by AQAST and the San Joaquin Valley Air Pollution Control District, with Jacob as co-organizer and featuring presentations by a number of AQAST PIs and Co-Is.
- Training workshops for AQ managers on the use of satellite data, organized in collaboration with ARSET including at U. Wisconsin (with Tracey Holloway) and in San Francisco (with Yang Liu).
- Physical Atmosphere Advisory Group workshops organized by Dick McNider on the improvement of physical parameterizations in regional AQ models using satellite data.
- Regular participation of AQAST members at meetings of the AQM community including AWMA, NACAA, WESTAR, LADCO, CenSARA, and EPA.
- Participation in sessions hosted by ASP, including the NASA Health and Air Quality Applications Program Review meetings in Newport, RI in 2012 (Loretta Mickley), St. Paul, MN in 2013 (Tracey Holloway) and Park City, UT in 2015 (Edward Hyer); the American Thoracic Society meeting in Denver 2015 (Holloway and Daven Henze); and the ASP-led session at the 2015 American Geophysical Union Meeting (Arastoo Pour Biazar, Holloway).

Website (http://www.aqast.org) . AQAST needed an attractive professional-level website as a window into its resources and activities to serve the AQM community. The initial plan was to have this website designed and curated at NASA but that turned out to be impractical because of limited staffing resources. Instead we hosted it at Harvard, with staffing supported by Jacob's leadership grant. The website features (1) listings of IPs and TTs with links, (2) recent news and a rotating picture gallery of AQAST highlights, (3) PI directory with pictures and blurbs describing expertise, (4) directory of AQM partners and associated projects, (5) publications and presentations with links, (6) meetings information. The website was updated with new material every month. Hosting the AQAST website outside NASA turned out to be beneficial as it allowed us to be in control of updates and also gave us more freedom on site content.

Twitter Account (@NASA_AQAST) and Media center (http://www.aqast-media.org/). In an effort to reach a broader audience of AQ managers, other stakeholders, scientists, and the public, in December 2012 we established a Twitter account listed as @NASA_AQAST. As of December 2015 the account had over 2300 followers and had posted over 1600 tweets. Twitter is a high-value outreach opportunity to connect with AQM agencies as most are active on Twitter, especially to announce air quality alerts; to connect with science journalists, most of whom are active on Twitter; and to connect with other NASA outreach initiatives. To provide content relevant to this wider audience, we established a secondary AQAST site, www.aqast-media.org. This second site, called AQAST Media Center, allowed for some advanced features, such as an embedded Twitter feed and attractive, flexible graphics. The AQAST Media Center posted original press releases, shared press releases with AQAST member institutions, links to popular press articles, and videos summarizing AQAST accomplishments. Although early efforts were

made to write and distribute original press releases, we found that our efforts were better directed toward our AQM audience, such as a series of AQAST stories illustrating partnerships with AQ managers and video summaries of meetings and outcomes.

Newsletters. The idea of publishing a regular AQAST newsletter originated from one of our AQM partners (Tom Moore of WRAP). 14 newsletters were produced over the AQAST tenure and distributed to the AQAST_News email list (559 subscribers). They featured reports on AQAST activities, meeting announcements, links to publications and presentations, and more. The first newsletters were produced as wiki-style pages, but subsequent newsletters were formatted as PDFs, with attractive layouts and pictures (http://acmg.seas.harvard.edu/aqast/newsletters.html and http://www.aqast-media.org/#!newsletters/c1dde). Copies were printed for distribution at AQAST meetings.

Feedback via ARSET. AQAST received information from ARSET on the issues faced by AQ managers attending ARSET training events. This information was based on a) the ARSET team's interaction with AQ managers during the training events, b) anonymous post-training surveys, and c) a wide-net satellite data end-user survey. Ana Prados (ARSET team lead), Pawan Gupta (ARSET), and Yang Liu (ARSET, AQAST) regularly conveyed this information to AQAST members at AQAST meetings. For example, one common request from AQ managers was for ready-made plots and analyses of satellite data for AQ applications. Feedback from ARSET led to AQAST review articles and websites (described in later sections) that were designed by AQAST members to facilitate the use of satellite data by the AQM community.

Special events. A number of special events were held to further publicize AQAST work. These included among others:

1. **Special session at AGU.** We organized a session and town hall at the Fall 2012 AGU, "Application of Satellite Data to Serve Air Quality Management Needs". We had 69 presentations submitted and were awarded a full day of oral sessions.
2. **Special issue of Environmental Manager.** We had a special issue of EM devoted to AQAST and featuring articles by AQAST PIs. Further details on the EM special issue are in Section 4.1.
3. **News conferences.** AQAST PIs Bryan Duncan, Russ Dickerson, and Anne Thompson received considerable media attention with two news conferences on the use of the OMI satellite instrument to monitor US and global trends in air quality. One was held at NASA/GSFC (10th anniversary of Aura launch) in July 2014 and the other at the Fall 2015 AGU.

4. AQAST outcome metrics

Several quantitative metrics can be used to measure the success of AQAST: (1) publications acknowledging AQAST funding, including in the journals and magazines of the AQM community, (2) involvement of AQ agencies as partners in AQAST projects, (3) participation at AQAST semiannual meetings, (4) AQAST following as measured by electronic and social

media. We present these different metrics below, along with related analysis based on a late 2015 survey of AQAST PIs and senior investigators[1].

4.1 Publications

A standard metric of outcome from a scientific program is the number of peer-reviewed publications acknowledging support from that program. Although AQAST's focus extended far beyond publications in its service to the AQM community, it is useful to start from this publications metric and examine what insights it lends. Over the 2011-2015 period, AQAST PIs produced 123 publications acknowledging funding from AQAST (Figure 2; the full list of papers with links is at http://www.aqast.org). During the mature stage of 2014-2015, AQAST PIs produced 40 publications per year, or more than 2 per PI per year. A third of AQAST publications in 2013-2015 were co-authored by two PIs or more, whereas there were no such co-authorships prior to 2013. This testifies to the vigor of collaboration within the Science Team, enabled in particular by the TTs.

Many of the AQAST publications were written explicitly to serve the needs of AQ managers, in particular by providing peer-reviewed documentation that would support regulatory action or response. Other publications focused on educating the AQM readership on the resources provided by Earth science data and tools. AQAST publications included 12 in *Environmental Manager (EM)* and 3 in the *Journal of the Air and Waste Management Association (JAWMA)*, which are standard trade magazines for AQ managers. A number of AQAST publications included AQ managers as co-authors, but any such metric would underestimate the depth of the partnership since AQ managers are often reluctant to be co-authors on scientific publications for a variety of reasons (lack of motivation, lengthy review process, concern of being associated with conclusions that could jeopardize regulatory actions). It is best here just to give a few examples of publications written with AQ managers (AQAST PIs and Co-Is in bold):

- Aburn, T., Jr., **R.R. Dickerson**, J.C.. Hains, D. King, R. Salawitch, T. Canty, X. Ren, **A.M. Thompson**, and M. Woodman, Ground-level ozone: a path forward for the eastern United States, Environmental Manager, May 2015.
- Lee, H.-M., F. Paulot, **D. K. Henze**, K. Travis, **D. J. Jacob,** L. H. Pardo, B. Schichtel, Sources of nitrogen deposition in Federal Class I areas in the US, Atmos. Chem. Phys., 15, 23089-23130, 2015.
- **Fiore, A.M**., J.T. Oberman, **M.Y. Lin**, L. Zhang, O.E. Clifton, **D.J. Jacob**, V. Naik, L.W. Horowitz, J.P. Pinto, G.P. Milly, Estimating North American background ozone in U.S. surface air with two independent global models: Variability, uncertainties and recommendations, Atmos. Environ., 96, 284-300, 2014.

[1] The survey was sent to AQAST PIs, and administered through the University of Wisconsin via the Qualtrics survey system. The survey was sent on December 26, 2015, and results analyzed on January 3, 2016. 13 of the 19 AQAST PIs responded, along with 2 senior scientists involved in AQAST (but not themselves PIs).

Of particular note also are two TT-led review papers published in the journal *Atmospheric Environment* to provide a tutorial to AQ managers on the value of satellite data for AQ applications (again, AQAST PIs or Co-Is in bold):

- **Streets, D.**, T. Canty, **G. Carmichael, B. de Foy, R. Dickerson**,, **B. Duncan, D. Edwards**, J. Haynes, **D. Henze**, M. Houyoux, **D. Jacob**, N. Krotkov, L. Lamsal, **Y. Liu,** Z. Lu, R. Martin, **G. Pfister,** R. Pinder, R. Salawitch, and K. Wecht, Emissions estimation from satellite retrievals: A review of current capability, Atmos. Environ., 77, 1011–1042, 2013.
- **Duncan, B.N.**, L.N. Lamsal, **Y. Liu, D.G. Streets**, P. Gupta, E. Hilsenrath, R.A. Kahn, J.E. Nielsen, A.J. Beyersdorf, S.P. Burton, **A.M. Fiore, J. Fishman, D.K. Henze,** C.A. Hostetler, N.A. Krotkov, A.I. Prados, **P. Lee, M. Lin**, S. Pawson, **G. Pfister**, K.E. Pickering, **R.B. Pierce,** Y. Yoshida, and L.D. Ziemba, Satellite data of atmospheric pollution for U.S. air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid, Atmos. Environ., 94**,** 647-662, 2014.

Each of these papers involved 10 AQAST PIs as co-authors. Streets et al. has been cited 38 times as of this writing and is recognized by the Web of Science as a "Highly Cited Paper" (top 1% in its field). Duncan et al. is the most downloaded Energy & Earth Science article published since January 2014.

Of further note is the AQAST special issue of *Environmental Manager* in February 2014 (Figure 3a). This issue contained 7 articles by AQAST PIs discussing different AQM applications of Earth science data and tools. EM is the trade magazine of the Air and Waste Management Association (AWMA). Having a special issue of EM devoted to AQAST was testimony to the acceptance of AQAST by the AQM community and how far we have gone in that regard.

Among the 15 respondents to the 2015 AQAST PI survey, publication numbers ranged from 1 to 16 over the course of AQAST (defined as publications on which the respondent is listed as a co-author on www.aqast.org). There is a positive relationship between publication productivity and an investigator's number of AQM partners, especially with the number of *new* AQM partners developed over the course of AQAST. The AQAST investigators who published more than 10 papers (n=4) had an average of 5 new AQM agencies with whom they had developed partnerships over the course of the grant. In contrast, investigators publishing between 6 and 10 papers (n=6) had an average of 4 new AQM partnerships, and investigators publishing 5 or fewer papers (n=5) had an average of 2.6 new AQM partnerships. The AQAST experience bears out the hypothesis that productive scientific output and stakeholder engagement are synergistic activities.

4.2 Air quality agency partners

All AQAST projects involved partnerships with specific AQ agencies, and all AQAST investigators significantly increased their engagement with AQM partners over the course of the grant. Prior to the launch of AQAST, participating PIs had between 0 and 6 existing AQM partnerships (averaging 1.7 over survey respondents). By the end of AQAST, all PIs increased the number of partnering agencies, and typically also the scope of personnel involved from a

given agency. At the conclusion of AQAST, PIs reported having between 1 and 16 AQM partnerships (averaging 5.7 over survey respondents).

Some of the specific projects through which AQAST partnered with AQM agencies are highlighted in Section 5 of this report and in AQAST newsletters (see Section 3.2 for links). All projects are posted on the AQAST website (click on the "Projects" tab), identifying the AQ agency partner and with links to the 1-page or 2-page descriptions. There were varying degrees of partnerships, from very active to more passive, including in particular:

- Direct regulatory work with agencies to assist with Integrated Science Assessments (ISAs), State Implementation Plans (SIPs), and filings for exceptional event designation;
- Education and training of AQ managers in the use of Earth Science data and tools through tutorials, meetings, and workshops, the latter often in collaboration with ARSET;
- Development and distribution of tools for use in AQ applications, such as for visualizing and accessing satellite data, or for designing policies to achieve both AQ and climate targets;
- Applications research to assess the impact of AQ regulations and to help design future regulations.

A first way to quantify the involvement of AQAST with AQ agencies is through the number of agencies partnering actively in AQAST projects. A list of these partners is given on the AQAST website http://acmg.seas.harvard.edu/aqast/partners.html including links to the specific AQAST projects with which they were involved. Figure 4 shows a map of these agencies and illustrates the range of involvement with AQAST from the federal to the local level. AQAST partners included 5 federal agencies, 9 regional agencies, 16 states, and 6 local (sub-state) agencies.

But simply considering active partners underestimates the depth of the AQM community engagement with AQAST. Through our publications, websites, newsletters, meetings, and social media, AQAST activities have had a widespread impact, changing community culture, and reaching a broad audience. The 2014 special AQAST issue of EM Magazine reached 9,000 readers and the AQAST Twitter feed reaches over 2,300 followers. Figure 5 shows a map of agencies having interacted with AQAST either as an active partner or as an AQAST meeting participant, representing a significant degree of engagement (most AQ managers attending AQAST meetings gave presentations at the AQ managers' session). The list includes 6 federal agencies, 12 regional agencies, 27 states, and 7 local agencies.

Table 2 gives a listing of all federal, regional, state, and local agencies having interacted with AQAST either as project partner or AQAST meeting participant. It shows the breadth of AQAST's footprint on the AQM community, and reflects the emphasis that AQAST placed on engaging state and local agencies.

Although difficult to quantify, our experience over the past five years is that AQAST is viewed as the "front door" to NASA from the perspective of local, state, and federal AQM professionals. This is apparent from the testimonials (Section 6), and the fact that AQAST members are now regularly invited to speak at meetings organized by air quality agencies including the 2013 WESTAR Meeting, the 2014 LADCO/CenSARA Meeting, the 2015 Western States Meeting,

and the upcoming 2016 LADCO/CenSARA meeting. These outcomes reflect the major investment that AQAST has made in building relationships with the AQM community.

4.3 Participation at AQAST meetings

Another metric of AQAST success is the participation at the semiannual AQAST meetings (AQAST#). Table 3 gives statistics and Figure 6 gives a bar chart of the number of meeting participants including breakdown by AQAST PI groups, other application scientists, AQ managers, industry, and NGOs. AQAST meetings were stand-alone meetings, not held in conjunction with any other meeting, so the numbers of participants provides a true measure of AQAST engagement. Statistics do not include the first AQAST meeting in May 2011 in Boulder, which was held as a breakout from the EPA Advanced Monitoring Initiative (AMI) meeting. That first meeting was mainly organizational as many groups had not received funding yet, and quantifying attendance was difficult to separate from the AMI meeting. Following that first meeting it was decided that AQAST meetings would be stand-alone. Although attendance could have been increased by organizing AQAST meetings in combination with another meeting, the focus on AQAST would have been diluted.

AQAST meetings averaged 78 participants. This included a stable representation of 40-50 participants from AQAST PI groups. Participation by other groups depended on the local constituency. Meetings held at EPA RTP had a large participation of EPA managers, and also (for AQAST10) of air quality scientists from nearby universities. AQAST 4 held at CARB had a large participation of California AQ managers. AQAST5 held at U. Maryland had a large participation from NASA/GSFC and NOAA/ARL. AQAST6 held in Houston had a large participation from industry. All meetings starting with AQAST3 had a strong representation of regional/state/local agencies. These agencies typically have very limited travel budgets and this was a major reason for diversifying AQAST meeting locations around the country.

4.4 AQAST following

Another metric of AQAST success in reaching out to the AQM community is the following and response through electronic media. Some statistics are shown in Table 4. The AQAST_News mailing list was set up to reach out to the AQM community with newsletters and meeting announcements. It presently has 559 subscribers. There are over 2300 followers on the AQAST Twitter account. As yet another measure of AQM community engagement, we received 62 responses from AQ managers to a poll conducted in Year 3 of AQAST requesting their assistance for selection of the TTs (section 3.1).

5. AQAST stories, products, outreach

The impact of a program like AQAST is difficult to measure solely by the quantitative metrics of Section 4. AQAST publications and meetings had a high impact, but there were many other components of service to the AQM community. Here we give some prominent examples. More

examples can be found in AQAST newsletters, the AQAST website, and the AQAST Media Center.

5.1 Spotlight stories

To provide visibility to AQAST service, we produced "spotlight" stories as magazine-type articles describing how activities of a particular AQAST PI have supported the AQM community, and featuring interviews with AQ managers. These stories were reported in the AQAST newsletters and are posted on the AQAST Media Center. Specific stories included:

- Interviews with Pat Dolwick of EPA/OAQPS and Joe Pinto of EPA/NCEA on how AQAST work by Arlene Fiore and Daniel Jacob contributed to the 2013 Ozone Integrated Science Assessment by providing high-quality background ozone estimates to support EPA's recommendation of tightening the ozone standard.
- Interview with Michael Geigert of the Connecticut Dept. of Energy and Environmental Protection, describing how interaction with AQAST through the delivery of satellite data and working with Pius Lee helped to improve his SIP and AQ forecasting work.
- Interview with Patrick Reddy of the Colorado Dept. of Public Health and Environment on how AQAST work by Gabriele Pfister (of David Edwards' team) during the FRAPPE aircraft campaign produced information critical for understanding and forecasting AQ along the Colorado Front Range.
- Interview with Tad Aburn of the Maryland Dept. of the Environment on how AQAST work with Russ Dickerson has been essential for their understanding of interstate transport affecting Maryland AQ.
- Interview with Mark Estes of the Texas Commission on Environmental Quality on how AQAST work with Dan Cohan enabled TCEQ to improve biogenic emissions for their SIP simulations.

5.2 Products

AQAST members developed and maintained several websites delivering Earth science products with a content and format designed for easy use by the AQM community. These efforts included:

- Websites managed by Greg Carmichael, Bryan Duncan, Tracey Holloway, and Jim Szykman to allow AQ managers easy visualization and quantitative delivery of AQ-relevant satellite data.
- The GLIMPSE on-line tool developed by Daven Henze to enable AQ managers to quantify the climate forcing impacts of AQ regulations.
- A statistical AQ forecast site for the state of Maryland developed by Anne Thompson by building on data collected in DISCOVER-AQ.

5.3 Outreach

Beyond service to the AQM community, AQAST had a mission to educate the public on AQ issues from its unique pulpit of NASA expertise including resources from Earth science data.

Activities over the years included press releases, news conferences, interviews, and public displays. Prominent examples included:

- Two press conferences (2015 Fall AGU, July 2014 10th Aura anniversary) in which Russ Dickerson, Bryan Duncan, and Anne Thompson reported long-term trends of OMI NO_2 as indicator of air pollution. These generated considerable media attention and follow-up interviews. An interview with Bryan Duncan went viral on the web.
- An OMI NO_2 lenticular produced by Bryan Duncan in a postcard-style format to show the decrease of NO_x emissions in the US. This lenticular was distributed at AQAST meetings and at news conferences, and it was hugely popular.
- The "Ozone Garden," a concept supported by AQAST under the direction of Jack Fishman, served as an education/public outreach demonstration that showed how damage is inflicted on plants and crops by ozone air pollution. Fishman developed the original prototype Ozone Garden in St. Louis in 2012, and by the end of the project, more than a dozen "Ozone Gardens" were started nationally, including those initiated by AQAST members Bryan Duncan, Daven Henze and Daniel Jacob. The project was featured on the cover of the August 2014 issue of the Bulletin of the American Meteorological Society (Figure 3b).

6. AQAST's impact on air quality management

6.1 Survey

As part of this retrospective, we surveyed U.S. air quality managers from local, state, and federal agencies to gain their perspective on AQAST. The survey was designed by AQAST Co-I Jana Milford. Results were analyzed by Daniel Knight, a social scientist at U. Colorado with no engagement in AQAST. The survey was distributed with assistance from the National Association of Clean Air Agencies (NACAA) and the Association of Air Pollution Control Agencies (AAPCA). These organizations sent email invitations to participate to members of their relevant technical committees. We also sent invitations to AQAST_News email list subscribers with government email addresses, and to air quality managers who were identified by AQAST researchers as current or past participants in AQAST Tiger Teams.

115 individuals responded to the survey, which was administered via Qualtrics over September 22 – October 6, 2015. 56% of the respondents reported that their agency had some involvement with NASA/AQAST activities; the rest reported no involvement. Findings from the survey are briefly summarized here, with additional results presented in the Appendix. We are currently following up the survey with a limited set of interviews of AQAST participants, and anticipate preparing a manuscript for publication in *Environmental Manager* on the combined survey and interview results.

As reflected in Figure 7, most respondents agreed or strongly agreed that AQAST meetings provided useful information and increased awareness of NASA-related research or tools. Just under half agreed or strongly agreed that the meetings had led to new collaborations. As reflected in Figure 8, most respondents agreed or strongly agreed that involvement with AQAST researchers helped create awareness of research and helped their agency's staff

access new resources or tools. Close to half indicated that the involvement led to new collaborations for their agency.

6.2 Testimonials

Appreciation for AQAST by the AQM community can be illustrated further by a sample of quotes from AQ managers. Additional quotes are available in the AQAST Spotlight stories (Section 5.1).

- "*AQAST's participation in EPA's stratospheric intrusion workgroup has been a big success… AQAST is being held up as an example of the type of relationship EPA would like to have with NASA….*" (Terry Keating, EPA)
- *"The N-deposition AQAST project will support the review of the secondary NAAQS…"* (Rich Scheffe, EPA)
- *"AQAST's Rapid Benefits Calculator alleviates a major limiting factor for quantifying the impacts of air pollutants around the world…"* (Susan Anenberg, EPA)
- "*AQAST helps us answer very important questions for the state…"* (Angie Dickens, Wisconsin DNR)
- *"The support from AQAST has provided enormous benefit for the Maryland ozone SIP…"* (George Aburn, MDE)
- "*AQAST improves the decision-making system…*" (Ajith Kaduwela, CARB)
- "*I applaud AQAST for developing techniques for using satellite data to improve modeling of the physical atmosphere…*'(Bright Dornblaser, TCEQ)
- "*Your work has been invaluable to us…In AQAST, we have a team of experts to turn to*" (Patrick Reddy, Colorado DPHE)
- *"AQAST allowed us to use state-of-science boundary conditions for our ozone SIP and document exceptional events* (Kenneth Lloyd, RAQC)

7. Lessons from the AQAST experience and recommendations

As demonstrated by the above metrics and highlights, AQAST has been a highly successful program. It has considerably increased the awareness, appreciation, and use of Earth science products (and in particular satellite data) by AQ managers. It has generated considerable goodwill between the AQM community and NASA, as shown by the consistent AQM community attendance at AQAST meetings.

Nowhere is the transformative impact of AQAST more evident than in the attitude of AQ managers at AQAST meetings. In the first meeting, the AQ managers were openly skeptical about the value of satellite data. We succeeded in completely turning around this attitude and it can now be stated without exaggeration that the AQM community is fully on board with AQAST.

In the survey of AQAST members, the most transformative aspect of AQAST was the emphasis on working directly with the AQM community. Relative to a standard project-based grant, investigators ranked the "emphasis on serving air quality managers" at 3.6 on a scale of 1-4, where 3 reflects having a "large effect" (relative to a traditional NASA research grant of the same duration and funding level) and 4 reflects being "transformative" to the activities. Other aspects ranked as impactful about the AQAST structure include the flexible funding to respond to emerging issues (ranked as 3.1), the regular AQAST meetings (3.1), access to colleagues and stakeholder partners (3.1), the Tiger Team structure (3.1), and the visibility of AQAST (3.0). Less emphasis was given to the emphasis on collaboration (2.9, where 2 = "some effect"), and access to NASA program managers (1.7, where 1 = "no effect").

Looking back at the whole of the AQAST experience, there are some aspects that were clear successes and others where there is room for improvement. There are useful lessons learned that may assist ASP in the design of future Applied Sciences teams. We elaborated on successes above. We describe below some specific challenges and offer recommendations.

Size of the team. AQAST was large, with 19 members. The original solicitation did not intend it to be that large. Size was both an asset and a liability. It allowed us to cast a wide net of interactions with AQ agencies and it contributed to the vibrancy of Science Team meetings. But it made it more difficult to oversee the activity of individual PIs, and it diluted somewhat the sense of mission. It also meant less money per investigator for TTs. It would have been possible to have an effective AQAST with a smaller team.
***Recommendation*:** Consider smaller Applied Sciences teams in the future.

Composition of the team. The expertise of the 19 AQAST PIs did not fully cover the scope of the team as sought in the original AQAST solicitation, and there was some replication of expertise between the PIs. This overlap facilitated collaborations, but limited the scope of problems that AQAST could address. In addition, some members had very little prior experience in either working with AQ agencies or working with Earth science products, and it was often a challenge for them to design appropriate AQAST projects at the interface.
Recommendation: Seek diversity in expertise within Applied Sciences teams.

Mandate of the team. As stated in the solicitation and reinforced by ASP management, AQAST was to have a broad mandate in using Earth science data and tools for AQ applications, not restricted to NASA products and not restricted to satellites. This was probably too broad a mandate. The transformative contribution that NASA can provide to application agencies is in the use of satellite data. Using satellite data is very challenging for AQ managers due to the size of the data, the unfamiliar variables, the need to accept and manage observational errors, and the implications for evaluating and improving models. This is where AQAST was most needed. However, without specific guidance to focus on satellite data, AQAST members could be tempted in delivering somewhat more routine products that augmented the capabilities of the AQM community but did not transform them. The fact that AQAST was "not just about satellites" probably helped to bring AQ managers into the AQAST tent, but it also encouraged some complacency on the part of PIs who could meet their AQAST obligations without addressing the real challenge of using satellite data for AQ applications.

Recommendation: Focus future Applied Sciences teams on the use of satellite data and their integration with suborbital data and models for addressing applications.

Continuity. A recurring question that we heard from the AQM community during the 5-year AQAST tenure was, "What will happen to our collaborative work after AQAST is over?". It is fortunate that H-AQAST will provide some continuity, through at a more limited level and with only partial overlap between AQAST and H-AQAST membership. It is important that H-AQAST be given a mandate to continue the relationships with the AQM community developed through AQAST.
Recommendation: Ensure long-term continuity in the relationships with stakeholder communities developed by Applied Science teams.

Tiger Team funding. The TTs were intrinsic to the functioning of AQAST as a team and were an invitation to engage the AQM community in the formulation of AQAST priorities. But we were hobbled by the uncertainty, lateness, and small size of TT funding. At the onset of AQAST we were told that TT funding would be $1.5M/year but it ended up being only $1M/year, which if you distribute among PIs amounted to little over $50K/year, and none in Year 5. Furthermore, this funding came so late as to weaken the concept of TTs as quick-response units. Every year we were told to have TTs selected and ready to go by October 1, but we did not know how much funding we would have and when it would materialize. The funding generally did not materialize until the next calendar year.
Recommendation: Make funding available for Tiger Teams steady, reliable, and timely.

Tiger Team selections. We struggled with the best formula for selecting TTs. After Year 2, when we had a selection process with less than 50% of proposed TTs selected, there was a feeling among AQAST members that having "winners and losers" was detrimental to AQAST team spirit. This led to the formula followed in Year 3 and beyond, where selection still took place but all PIs were invited to participate in the selected TTs. This diluted the focus. Looking back, it seems that a better formula would be not to have AQAST members serve as TT proposal reviewers and instead fully rely on the AQM community (which was fully willing to do this). This would have produced more focused and responsive TTs, with winners and losers but avoiding hard feelings within the team. The team would still have provided oversight of the TT proposals in their initial phase by approving their value as AQAST projects at the interface of Earth science and AQM.
Recommendation: Have TT selection done by the applications stakeholder community, using the 2-stage process of open polling and panel review, with oversight from the Team leadership.

Travel support to attend Science Team meetings. Three of the AQAST PIs were unfunded, because they were civil servants at other agencies, but this lack of funding extended to travel which made it sometimes impossible for them to attend AQAST meetings. In addition, lack of travel resources at AQ agencies was often a limiting factor in their ability to attend AQAST meetings. Providing some travel support would show engagement and goodwill on NASA's part at little cost.
Recommendation: Set aside some Team funds to invite application managers to meetings, and ensure travel support for all Team members.

Stakeholder diversity. The emphasis of AQAST, particularly in the early years, was to build relationships with AQ regulatory agencies. This led to complaints from industry groups that they were being ignored, and indeed these groups have different and interesting perspectives to bring on AQ problems. We made an effort to reach out to them and had participation at later AQAST meetings of the Electric Power Research Institute (EPRI), the American Petroleum Institute (API), and individual companies, though we never developed active partnerships with these groups. We also had occasional participation in our meetings from NGOs such as the Sierra Club and it would have been valuable to encourage this participation more. We also would have gained from reaching out more to consulting companies that contract with the states on applications of AQ models.
Recommendation; Encourage future Applied Science teams to develop relationships with the full spectrum of stakeholders including government agencies, consulting companies working with these agencies, industry groups, and NGOs.

Communicating results to stakeholders. Some AQAST projects engaged AQM partners in the formulation of the project but then failed to properly communicate the results in a way that could serve the interests not just of the partners but also the broader AQM community. There could have been more diligence on the AQAST side to ensure that the partners had gotten what they wanted out of their projects. It would have also been good to post results of completed projects on the website (bullet points, with links to publications and other materials).
Recommendation. Applied Science teams should ensure proper communication of project results to their stakeholder community, beginning with their project partners and extending to the broader community.

Feedback from ASP. ASP managers were always present at AQAST meetings, which was very much appreciated, but provided limited feedback on how AQAST was meeting its goals, what should be improved, etc. We took the hands-off approach as a sign that we were doing things right but some more positive reinforcement or criticism would have helped. We would also have appreciated more opportunities to advertise AQAST work through NASA channels and tell ESD managers about the great work that we were doing. We appreciated being finally connected with the Monthly Status Review process in 2015; it would have been useful to be connected earlier.
Recommendation: Provide more feedback from the ASP leadership to the Applied Sciences teams, and provide opportunities for teams to advertise their work at NASA.

8. Closing thoughts

AQAST was designed to be a prototype for future ASP Science Teams. We close this report by reflecting on the value of such Science Teams as informed by our experience.

A unique feature of AQAST, within ASP and more broadly from the perspective of other NASA Science Teams, is that it was not built around a specific deliverable or to support a specific field or satellite mission. It had a broader mandate to exploit Earth science products in support of AQM applications, with the flexibility to respond the evolving needs of the AQM community. As such, investigators were able to address emerging issues without the delay and rigidity that would be associated with a standard ROSES program. This flexibility made AQAST very interesting to its members and contributed to an excellent team spirit. It was also very attractive

to the AQM community, who could recruit AQAST members to work on their specific problems of interest and develop relationships. Indeed, the issues of concern to the AQM community evolved rapidly over the 5-year tenure of AQAST. Concerns over background ozone, AQ-climate interactions, agricultural emissions, oil/gas emissions, open fires, methane took on increasing importance. These and other concerns involved not only national policy but also "what's-in-my-backyard" questions from local agencies. AQAST would not have been able to respond to the evolving needs and questions from the diverse AQM community without its flexible mandate. The success of AQAST validated ASP's vision for Applied Sciences teams.

By design and as reflected in its mandate, AQAST delivered on a wide range of small-scale projects rather than on a few selected large-scale projects. In doing so, it was able to reach out to a large number of AQ agencies. Indeed, a distinguishing feature of AQAST was its success in working with regional/state/local agencies. This level of stakeholder engagement would not have been possible within the framework of a regular ROSES program, or if the team had been tasked with delivering on a large-scale project or on transition to operations. From this perspective, the most important legacy of AQAST is the development of a network of relationships with a large number of AQ agencies, and the recognition by these agencies of the value of Earth science products. The "AQAST brand" is now well known and appreciated across the diverse web of AQ agencies, which are now increasingly turning to Earth science products for their applications. An example has been the growing use of satellite data by state agencies for their SIPs and for their exceptional event demonstrations.

The need to exploit satellite data effectively for AQM applications will become even more pressing in the future. Satellites have a unique role to play in addressing emerging AQM issues such as background ozone, agricultural and oil/gas emssions, year-to-year emission trends, greenhouse gas fluxes, and long-range transport of fire and dust plumes. As observations from the first generation of NASA Earth science satellites (Terra, Aqua, Aura) progressively decay, it will be important to demonstrate the continuity of observations for AQM applications from the fleet of operational satellites (OMPS, VIIRS, GOME-2, IASI instruments) as well as the exciting new opportunities from the TROPOMI instrument (7x7 km^2 nadir resolution) to be launched in 2016. It is also crucial to prepare the AQM community to exploit effectively the revolutionary geostationary data that will be produced by TEMPO (launch in 2019-2021 time frame).

Maintaining the deep relationships developed by AQAST with the AQM community is essential for AQAST's legacy and to the accumulated reservoir of goodwill toward NASA. The AQM community has come to count on AQAST and needs continuity in support of its operations. But maintaining continuity is always a challenge at NASA because of the need to focus on research and innovation, and we recognize that the success of AQAST should motivate the creation of ASP Science Teams in other areas of applications. We are very pleased by the recently released H-AQAST solicitation, which maintains the presence of AQAST albeit in a more limited way. We look forward to seeing AQAST live on in the form of H-AQAST.

Table 1. AQAST Principal Investigators

Principal Investigator	*Institution*	*General expertise*
Daniel Jacob (leader)	Harvard	Satellite data, global modeling, chemistry-climate
Tracey Holloway[1]	U. Wisconsin	Satellite data, regional modeling
Greg Carmichael	U. Iowa	Regional modeling, forecasting
Dan Cohan	Rice	Satellite data, regional modeling
Russ Dickerson	U. Maryland	Satellite/aircraft/surface data, regional modeling
Bryan Duncan	NASA/GSFC	Satellite data, global modeling
David Edwards	NCAR	Satellite data, global/regional modeling
Arlene Fiore	Columbia	Global modeling, chemistry-climate
Jack Fishman	Saint Louis U.	Pollution damage to vegetation, E/PO
Daven Henze	U. Colorado	Regional/global modeling
Edward Hyer	NRL	Satellite aerosol data, global modeling
Pius Lee[2,3]	NOAA/ARL	Regional modeling, forecasting
Yang Liu	Emory	Satellite aerosol data, health effects
Dick McNider	U. Alabama	Regional physical modeling
Brad Pierce[2]	NOAA/NESDIS	Satellite data, regional/global modeling
Ted Russell	Georgia Tech	Regional modeling, forecasting
David Streets	Argonne Nat'l Lab	Emission inventories
Jim Szykman[2]	EPA	Data services
Anne Thompson	Penn State/NASA[4]	Ozonesondes, surface observations

[1]Apppointed deputy leader by Jacob in Year 2
[2]Funded for Tiger Team activities only
[3]In replacement of Daewon Byun (NOAA/ARL), who was selected but died shortly afterward
[4]Moved from Penn State to NASA GSFC during appointment

Table 2. Air quality agencies involved with AQAST as project partners or AQAST meeting participants

Federal

Bureau of Land Management (BLM)
Center for Disease Control (CDC)
Environmental Protection Agency (EPA)
National Oceanic and Atmospheric Admin. (NOAA)
National Park Service (NPS)
US Department of Agriculture (USDA)

Regional

Central States Air Resources Agencies (CenSARA)
Environmental Protection Agency (EPA) Region 2
Environmental Protection Agency (EPA) Region 4
Environmental Protection Agency (EPA) Region 5
Environmental Protection Agency (EPA) Region 8
Environmental Protection Agency (EPA) Region 9
Lake Michigan Air Directors Consortium (LADCO)
Mid-Atlantic Regional Air Management Assoc. (MARAMA)
Northeast States for Coordinated Air Use Mgmt (NESCAUM)
Ozone Transport Commission (OTC)
Southeastern Air Pollution Control Agencies (SESARM)
Western Regional Air Partnership (WRAP)

State

Alabama Department of Environmental Management
California Air Resources Board
California Energy Commission
Colorado Department of Public Health and Environment
Connecticut Dept of Energy and Environmental Protection
Delaware Department of Natural Resources and Conservation
Georgia Department of Natural Resources
Georgia Environmental Protection Division
Georgia Forestry Commission
Idaho Department of Environmental Quality
Illinois Environmental Protection Agency
Iowa Department of Natural Resources
Maine Department of Environmental Protection
Maryland Department of the Environment
Maryland Department of Natural Resources
Massachusetts Department of Environmental Protection
Missouri Department of Natural Resources
Nevada Division of Environmental Protection
New Hampshire Department of Environmental Services
New Jersey Department of Environmental Protection
New York State Department of Environmental Conservation
New York State Energy Resources Development Admin.
North Carolina Department of Environmental Quality
Ohio Environmental Protection Agency
Oklahoma Department of Environmental Quality
Rhode Island Department of Environmental Management
Texas Commission on Environmental Quality
Utah Department of Environmental Quality
Vermont Department of Environmental Conservation
Virginia Department of Environmental Quality
Wisconsin Department of Natural Resources
Wyoming Department of Environmental Quality

Local

Bay Area Air Quality Management District
Clark County Department of Air Quality
East-West Gateway Air Quality Advisory Committee
Maricopa County Air Quality Agency
Sacramento Air Quality District
San Joaquin Valley Air Pollution Control District
South Coast Air Quality Management District

Table 3. Participation at AQAST meetings[1]

	AQAST2 EPA RTP Nov 2011	AQAST3 U. Wisc. Jun 2012	AQAST4 CARB Dec 2012	AQAST5 U.Maryland Jun 2013	AQAST6 Rice U. Jan 2014	AQAST7 Harvard Jun 2014	AQAST8 Ga. Tech Dec 2014	AQAST9 Saint Louis U. Jun 1015	AQAST10 EPA RTP Jan 2016
AQAST	26	39	32	50	41	44	51	45	48
Other science	0	5	12	38	16	18	6	6	48
AQ agencies									
federal	12	0	0	8	2	4	4	0	30
regional	0	3	2	2	2	2	1	7	4
state	1	5	16	11	3	4	5	4	6
local	0	0	5	0	1	1	1	0	0
Industry	0	1	1	1	10	3	1	1	3
NGOs	0	0	0	2	1	3	0	2	1
Total	39	53	68	112	76	79	69	65	140

[1]As estimated from registration lists.

Table 4. AQAST following on electronic media

Vehicle	*Purpose*	*Numbers*
AQAST_News mailing list	Newsletters, meeting announcements	559 subscribers
AQAST Twitter account	News (over 1600 tweets)	2300 followers
AQAST poll to AQ managers	Input on Tiger Team selections	62 AQM respondents

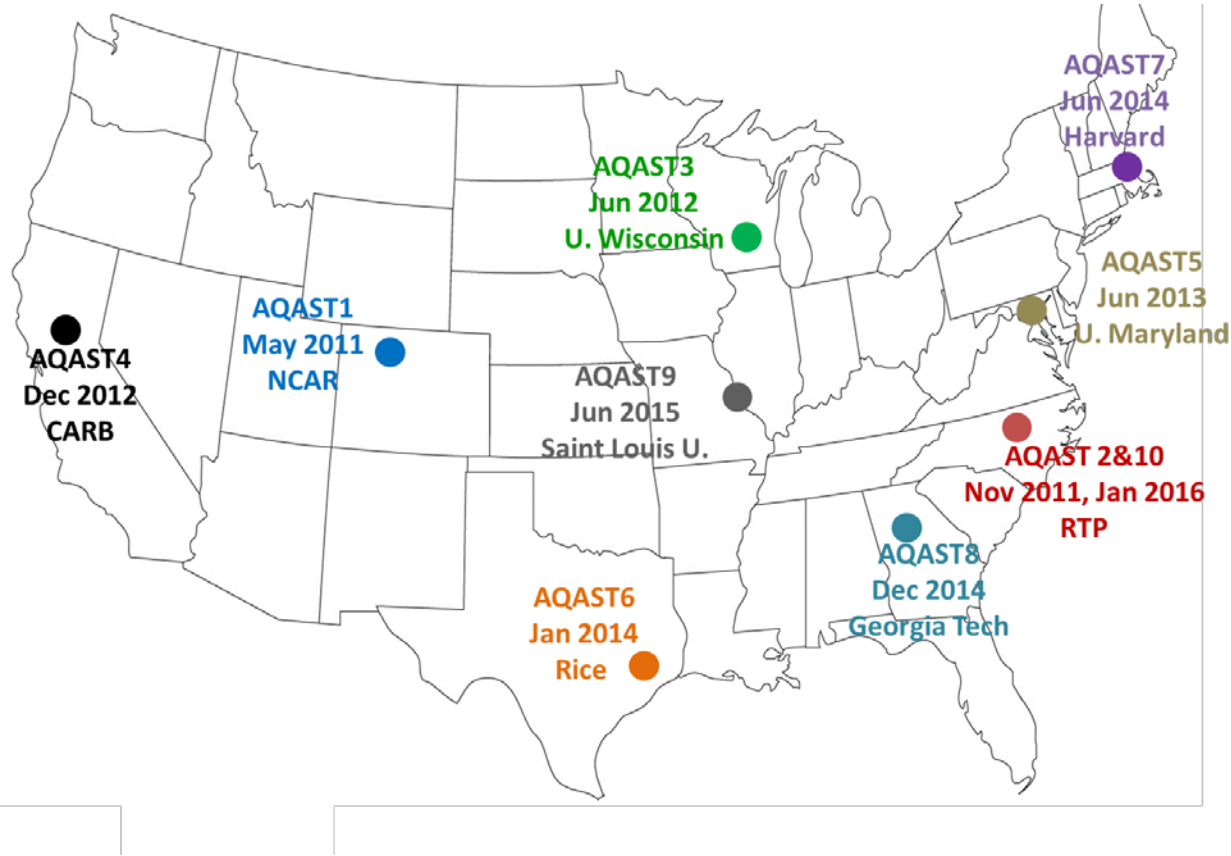

Figure 1, Semiannual AQAST meetings. Meeting presentations are posted at http://www.aqast.org

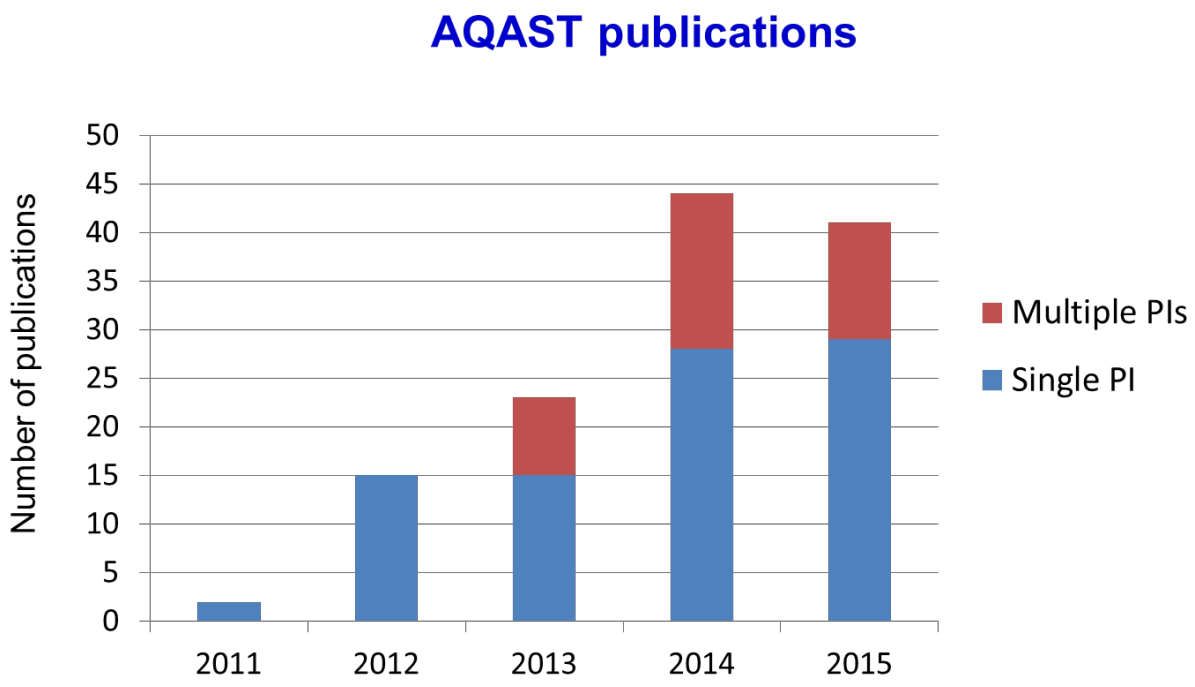

Figure 2. Publications acknowledging funding from AQAST. “Multiple PIs” publications included two or more AQAST PIs as co-authors. All publications are posted with links at http://www.aqast.org

Figure 3a. Cover of the February 2014 AQAST special issue of *Environmental Manager*

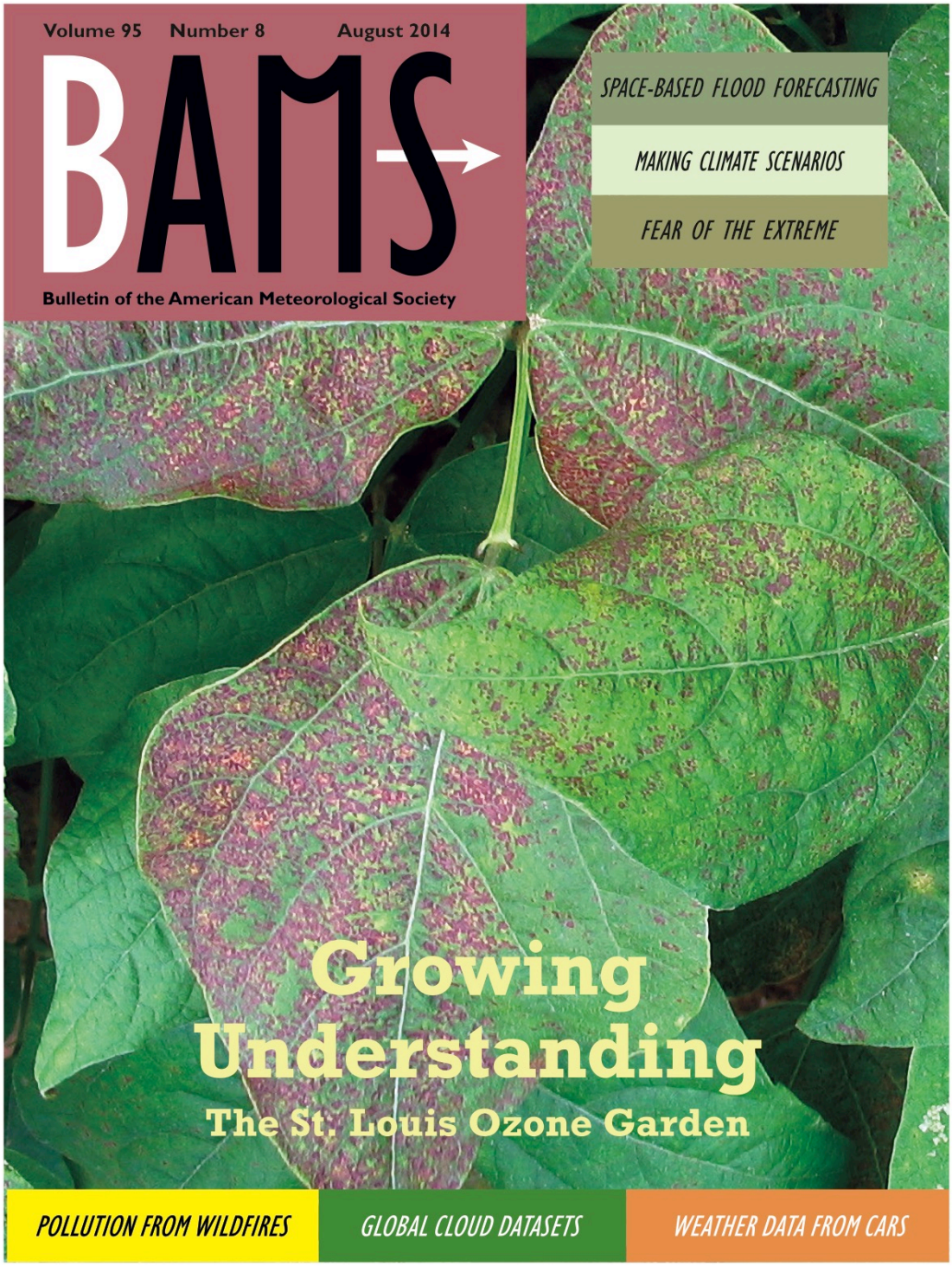

Figure 3b. Cover of the August 2014 *Bulletin of the American Meteorological Society* featuring an AQAST-sponsored education/public outreach program.

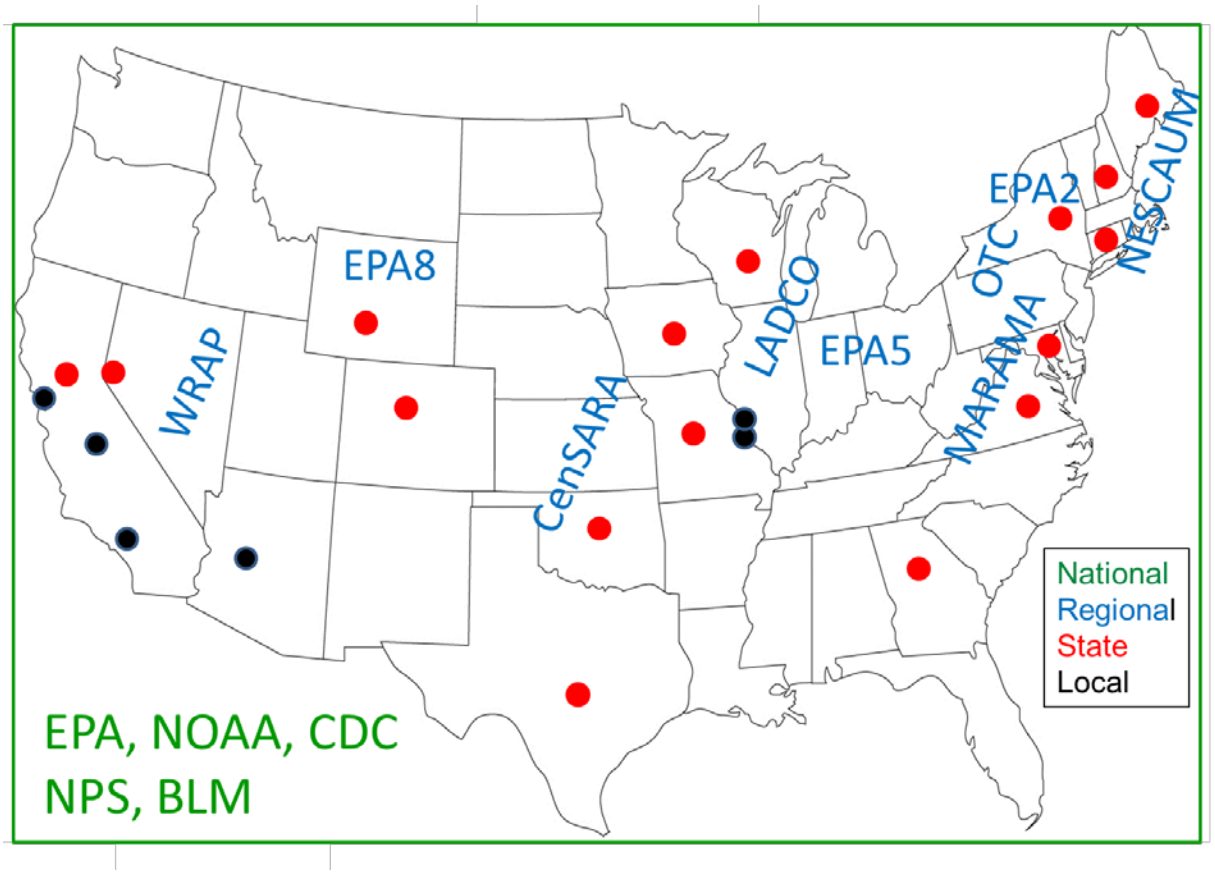

Figure 4. Air quality agencies partnering actively in AQAST projects. The agencies are listed on the AQAST website (http://www.aqast.org , "Partners" tab) with links to their specific projects.

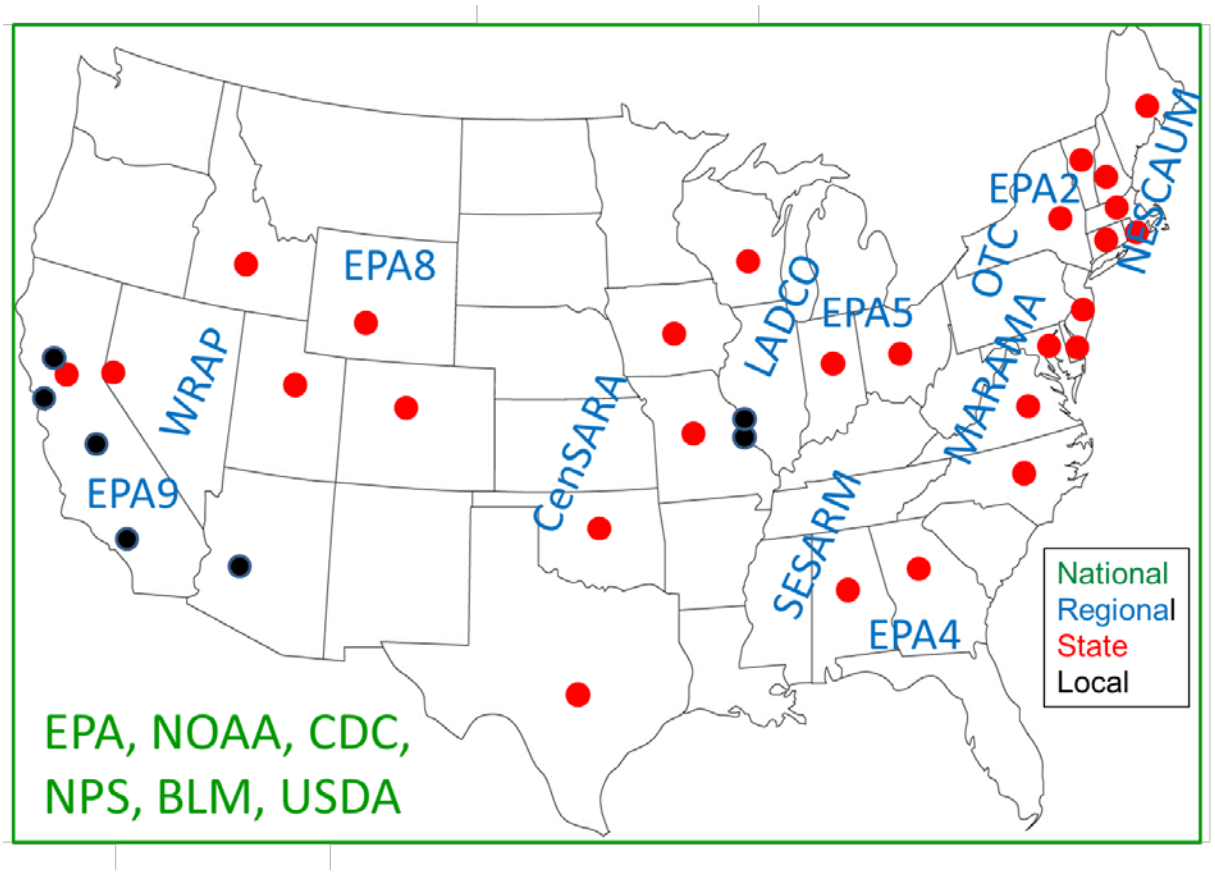

Figure 5. Air quality agencies interacting with AQAST as project partners or AQAST meeting participants (Table 2).

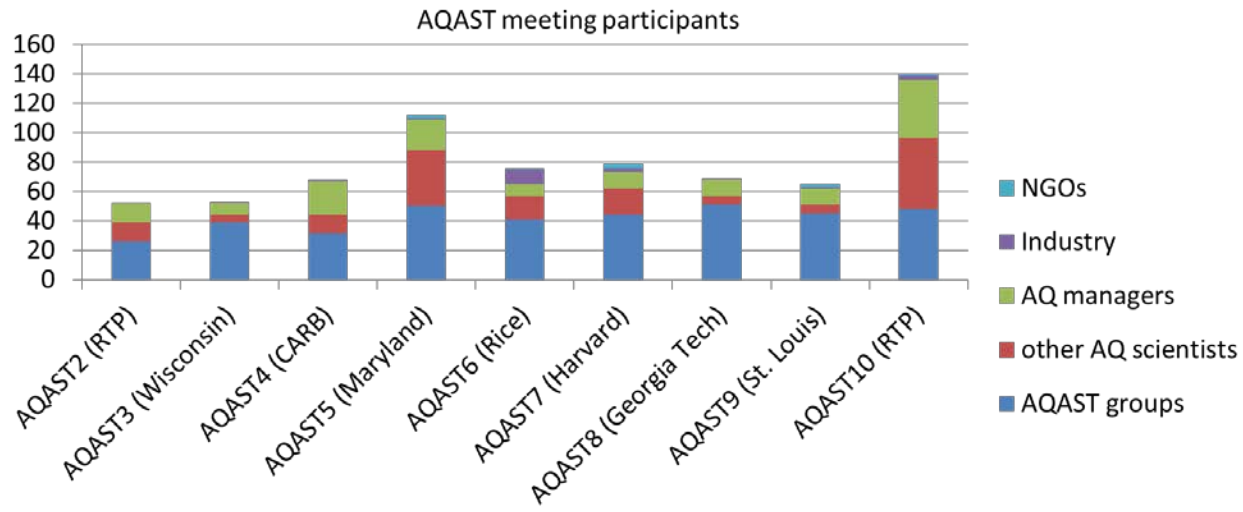

Figure 6. Participants at AQAST meetings.

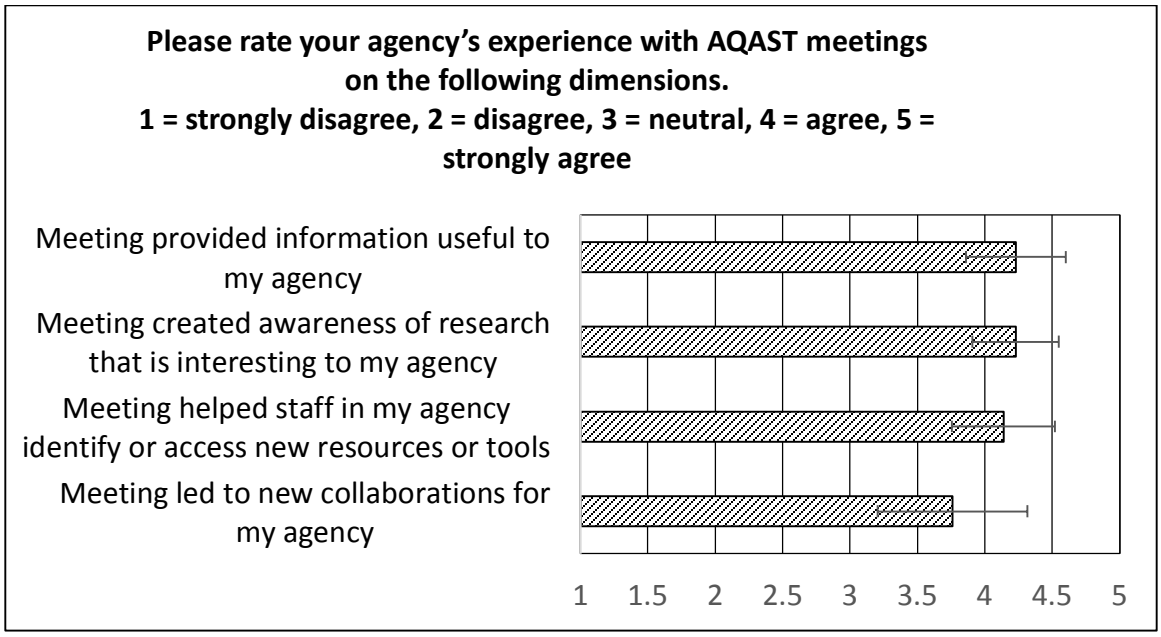

Figure 7. Mean and standard deviation of air quality managers' survey responses regarding their experience with AQAST meetings (n = 54).

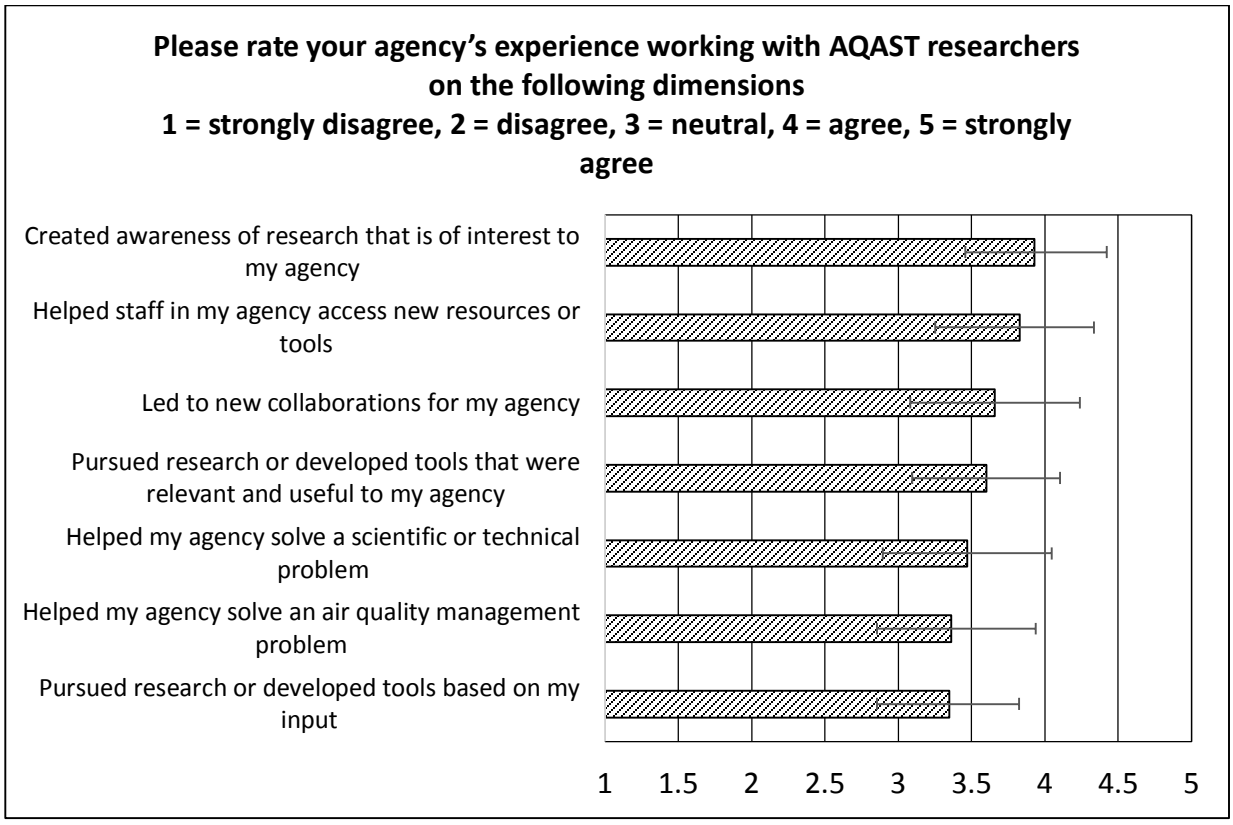

Figure 8. Mean and standard deviation of air quality managers' survey responses regarding their experience working with AQAST researchers (n = 53).

Appendix: Survey of AQAST's impact on air quality managers

A.1. Introduction

As part of a 4th year Tiger Team effort to evaluate AQAST, we developed and administered a survey of U.S. air quality managers. Survey design was guided by the goals and objectives of the AQAST program, focusing on the question of how AQAST has affected air quality managers' use of NASA's Earth science observations, models, and research results. The survey was developed by Jana Milford and Daniel Knight; and revised with feedback from Tracey Holloway, Bryan Duncan, Tom Moore, Pat Dolwick, and Teresa Pella.
AQAST goals considered in developing the survey were:

1. Develop close partnerships with air quality managers at the local, state, regional, and national levels
2. Conduct air quality research
3. Produce satellite, aircraft and surface site data products
4. Connect stakeholders through annual AQAST projects and events

The survey was administered via Qualtrics from September 22 – October 6, 2015. The survey was distributed with assistance from the National Association of Clean Air Agencies (NACAA) and the Association of Air Pollution Control Agencies (AAPCA). These organizations sent email invitations to participate to members of their relevant technical committees. We also sent invitations directly to subscribers to AQASTs email list with government email addresses, and to air quality managers who were identified by AQAST researchers as current or past participants in AQAST Tiger Teams.

We are currently conducting a limited set of interviews to follow-up on survey responses. Preliminary results from the survey are discussed below.

A.2. Who responded to the survey?

One hundred and fifteen individuals responded to the survey. As shown in Table A1, approximately 60% of the respondents identified themselves as working for a state or tribal-level environmental or public health agency; 22% for a county or local-level environmental or public health agency; 11% for a regional or other multi-jurisdictional organization; 4% for the U.S. Environmental Protection Agency and 2% for another federal agency. Respondents were distributed across the U.S., representing all 10 EPA regions (Table A2), with the greatest numbers of respondents indicating they were from EPA Regions 9 (AZ, CA, HI, NV, 22%), 4 (AL, FL, GA, KY, MS, NC, SC, TN, 14%), and 10 (AK, ID, OR, WA, 13%). Twenty-six percent of respondents reported having 10 or fewer years of experience in the air quality field; 26% between 11 and 20 years of experience; and 48% 20 or more years of experience (Table A3). The air quality management activities in which survey respondents reported being involved (e.g., technical support, strategic planning, administration) are shown in Table A4.
As shown in Table A5, approximately 64% of respondents indicated they or someone from their agency had heard presentations on the use of satellite data; 87% indicated they or someone from their agency had read papers on the use of satellite data; and 37% said they or someone from their agency had been involved in NASA training on using satellite data. About 44% of respondents indicated someone from their agency had attended AQAST meetings; 24% indicated

someone had been involved in AQAST research activities; and 17% reported involvement with Discover AQ campaigns. Overall, 56% of the respondents reported that their agency had some involvement with NASA/AQAST activities; 44% reported they had no involvement.

A.3 What air quality management challenges are top priorities?

The first set of survey questions asked what air quality management challenges are currently faced by air quality agencies, and which challenges are their top priorities for improved scientific or technical information.

As shown in Table A6, the top challenges reported by survey respondents are meeting the National Ambient Air Quality Standards (NAAQS) for ozone, emissions from mobile sources, interstate air pollution transport, and meeting the NAAQS for particulate matter (PM). International transport of air pollution, emissions from oil and gas activity, and nitrogen deposition were reported as important challenges by some agencies in some regions, but were not as widely identified in the others. Respondents from state or tribal agencies generally ranked emissions from oil and gas activity as a greater challenge than did respondents from county or local agencies. Respondents from regional planning/multijurisdictional agencies generally ranked emissions from mobile sources as a greater challenge than did respondents from state/tribal or county/local agencies.

The next question asked respondents to identify the three air quality challenges for which their agency was most in need of improved scientific or technical information. Responses to this question (Table A7) indicated that the needs for improved information generally correspond to the top challenges: meeting the NAAQS for ozone, emissions from mobile sources, interstate air pollution transport, and meeting the PM NAAQS. Emissions of greenhouse gases ranked higher as a management challenge than as an area in need of improved information.

A.4 What technical tools and resources are top priorities?

The next set of survey questions sought to understand what scientific or technical tools and resources are being used in air quality management, including satellite data, and which of them are top priorities for improvement.

As shown in Table A8, survey respondents reported the data/tools they use most frequently are surface monitoring data, emissions inventories, and air quality models. About two-thirds of all respondents said they use these data/tools frequently. About 24% of respondents said they never or infrequently use satellite data; 36% said they use it occasionally; and 40% said they use it more often or frequently. About 53% of respondents said they never or infrequently use aircraft or special campaign data; 24% said they use it occasionally; and 13% said they use it more often or frequently. County or local level respondents were more likely to indicate they often use air quality forecasts than state/tribal level respondents.

We followed the question on frequency of use with the question “of the types of scientific or technical resources you use, which three have the greatest need for improvement?” The survey responses (Table A9) indicate that the priorities for improved information deviate in rankings from the frequency of use of these resources. Air quality models and emissions inventories were

most often listed among the three having the greatest need for improvement. Estimates of interstate or international transport and satellite data rank third and fourth, respectively, in terms of how often they were identified as top priorities for improvement. Surface monitoring was identified as frequently used, but is not rated as a top priority for needing improvement.
The next question asked specifically about use of resources related to NASA and AQAST, including specific types of satellite data, modeled estimates of pollutant transport, and air quality forecasts. As shown in Table A10, more than half of the respondents reported that their agency used each of the listed technical resources, except for data from Discover AQ campaigns. The more limited use of the Discover AQ data is not surprising, since those campaigns have been limited in their geographic coverage. The most widely used resources are satellite observations of smoke and NOAA's national air quality forecasting capability, both of which are identified as being used for public information. Other uses of the listed resources that were mentioned by several respondents in open-ended written responses include use in analyzing pollution episodes/exceptional events (15 written responses); smoke management (5 written responses); and general data analysis (4 written responses).

Following up on our inquiries about the use of satellite data, we then listed several potential issues and asked which had been or still were barriers to the respondent's organization's use of those data. Table A11 lists the issues and indicates how the responses differed between respondents reporting that their agency had some involvement with AQAST and those that did not. Across all respondents, the top three barriers to the use of satellite data were inadequate coverage or frequency; data uncertainty; and lack of staff time or resources to process and acquire the data. Though not significant, some of the differences in responses between AQAST participants and non-participants are interesting. For example, fewer AQAST participants than non-participants identified "lack of relevance to air quality management" as a barrier (24% versus 41%). More AQAST participants than non-participants identified as barriers "hard to find out what data are potentially available or useful" (76.7% versus 50%) and "staff lack necessary training and expertise to acquire and process data (74% versus 53%).

A.5. What impact has AQAST had?

The next set of questions was administered only to the 56% of the survey respondents who indicated that their agency or someone within their agency had some involvement with AQAST. We started this segment of the survey with questions about outcomes from AQAST meetings and from working with AQAST researchers.

In response to a request to "rate your agency's experience with AQAST meetings" on several dimensions (Table A12), most respondents agreed or strongly agreed that the AQAST meetings had provided useful information and increased awareness of research or tools. Just under half agreed or strongly agreed that the meetings had led to new collaborations (the remaining respondents either said they disagreed, were neutral, or didn't know.)

In response to a request to "rate your agency's experience working with AQAST researchers" (Table A13) more than half of those answering agreed or strongly agreed that involvement with AQAST researchers helped create awareness of research and helped their agency's staff access new resources or tools. Close to half indicated the involvement led to new collaborations for

their agency. The ratings on these outcomes are generally highest for the relatively less individualized outcomes of creating awareness of research and providing access to new tools or resources, and are lowest for more specifically directed outcomes including pursuing research based on the respondent's input.

We next asked for written responses to the question "if an AQAST meeting or research team helped your agency access new resources, tools or research results, please list those outcomes." Eleven of the fifteen written responses to this request mentioned improved access to satellite or field data or modeling tools. The remaining responses said that that the respondents see potential for future benefit.

The next question asked "has anything changed in your practice of air quality management as a result of interactions with the AQAST team?" Although we wrote this question to focus on management practices, as distinct from technical tools and scientific information, in the aggregate the responses were similar to those for the previous question. Nine of the 21 written responses to this second open-ended question mentioned improved access to data or tools or improved understanding of air quality phenomena. Ten of the responses indicated that there have not yet been any changes in their agency's practice of air quality management.
Lastly, we asked the open-ended question "how could NASA/AQAST improve its engagement and support for air quality management agencies?" Six of the 24 written responses to this question mentioned continued or greater focus on tool development. Two responses mentioned specific research topics. Seven responses emphasized the role NASA could play in providing training. Four responses recommended greater input from states/air quality management agencies and four recommended greater transparency e.g., identifying the limitations of AQAST products and activities (as well as their strengths).

Table A1. Percentage of respondents who reported working for the specified type of agency

State or tribal-level environmental or public health agency	58.5%
County or local-level environmental or public health agency	22.3%
Regional planning organization or other multi-jurisdictional organization	10.6%
EPA	4.3%
Other federal environmental, public health, or land management agency	2.1%
Other	2.1%

Table A2. Percentage of respondents who reported working in the specified EPA Region

1	2	3	4	5	6	7	8	9	10
4.7%	3.5%	7.0%	14.0%	10.5%	11.6%	5.8%	8.1%	22.1%	12.8%

Table A3. Percentage of respondents by reported years of experience in the air quality field

1 – 10	26.1%
11 – 20	26.0%
>20	47.9%

Table A4. Percentage of respondents who reported involvement with the specified activities in their current position

Activities	Overall Percent	AQAST-involved Percent
Technical support- modeling	51.0%	44.2%
Strategic planning	43.0%	53.5%
Policy development	41.0%	51.2%
Technical support- emissions inventory development	39.0%	32.6%
Technical support- monitoring	34.0%	44.2%
Technical support- meteorology or forecasting	34.0%	32.6%
Administration or management	33.0%	44.2%
Public or stakeholder outreach	31.0%	46.5%
Other (Please Specify)	15.0%	9.3%
Permitting	11.0%	20.9%
Inspections and compliance assistance	8.0%	14.0%

Table A5. Percentage of respondents who reported that their agency or someone from their agency had been involved in the specified activities

NASA Programs	Yes
1. Read papers on use of satellite data	86.7%
2. Heard presentation(s) on use of satellite data	63.5%
3. AQAST meetings	43.5%
4. Other NASA programs	41.7%
5. NASA's training on satellite data	36.5%
6. AQAST research projects	23.5%
7. NASA Discover AQ campaigns	17.4%

Table A6. Mean and standard deviation of responses to the question "which air quality management issues are active challenges for your agency?" 1 = not an issue, 2 = somewhat challenging, 3 = more challenging, 4 = major challenge

Issues	Mean, 4 point scale	Std. Deviation
1. Ozone NAAQS attainment or maintenance	3.39	.873
2. Emissions from transportation/mobile sources	3.14	.853
3. Interstate transport of air pollution	3.07	.927
4. Particulate Matter NAAQS attainment or maintenance	2.96	.999
5. Emissions of greenhouse gases	2.86	.985
6. Attribution of uncontrollable sources to exceptional events	2.80	.984
7. Fires and smoke management	2.72	1.013
8. Regional haze or visibility	2.68	.864
9. Emissions of hazardous air pollutants	2.63	.935
10. Emissions from power plants	2.52	1.052
11. International transport of air pollution	2.51	1.070
12. Emissions from oil and gas activity	2.22	1.148
13. Nitrogen deposition and ecosystem impacts	2.21	.958

Table A7. Percentage of respondents who included each item in response to the question, “for which three air quality management issues does your agency have the greatest need for improved scientific or technical information?”

Challenges	Percent
1. Ozone NAAQS attainment or maintenance	49.6%
2. Interstate transport of air pollution	38.3%
3. Emissions from transportation/mobile sources	31.3%
4. Particulate Matter NAAQS attainment or maintenance	26.1%
5. Attribution of uncontrollable sources to exceptional events	20.9%
6. Fires and smoke management	20.0%
7. International transport of air pollution	18.3%
8. Emissions from oil and gas activity	18.3%
9. Emissions of greenhouse gasses	14.8%
10. Emissions of hazardous air pollutants	13.0%
11. Regional haze or visibility	8.7%
12. Emissions from power plants	8.7%
13. Nitrogen deposition and ecosystem impacts	7.8%

Table A8. Mean and standard deviation of responses to the question "In order to carry out your professional responsibilities, which types of scientific or technical information do you use?" 1 = never, 2 = infrequently, 3 = occasionally, 4 = more often, 5 = frequently

Tools	Mean, 5 point scale	Std. Deviation
1. Surface monitoring data	4.45	.940
2. Emissions inventories	4.45	.863
3. Air quality models	4.41	.900
4. Air quality forecasts	3.92	1.261
5. Meteorological forecasts	3.89	1.267
6. Assessments of emissions trends	3.82	1.039
7. Source emissions reports	3.60	1.241
8. Satellite data	3.27	1.136
9. Estimates of interstate or international transport	3.23	1.195
10. Information on costs and effectiveness of control measures	3.17	1.202
11. Transportation plans and projections	3.08	1.109
12. Health effects information	3.06	1.053
13. Source inspection reports	3.01	1.439
14. Aircraft data and other measurements from special field campaigns	2.29	1.055
15. Personal exposure monitoring data	2.08	.986

Table A9. Percentage of respondents who included each item in response to the question, “of the types of scientific or technical resources you use, which three have the greatest need for improvement?”

Tools	Percent
1. Air quality models	56.5%
2. Emissions inventories	48.7%
3. Estimates of interstate or international transport	32.2%
4. Satellite data	19.1%
5. Air quality forecasts	16.5%
6. Assessments of emissions trends	13.9%
7. Information on costs and effectiveness of control measures	13.9%
8. Meteorological forecasts	13.0%
9. Health effects information	10.4%
10. Surface monitoring data	9.6%
11. Aircraft data and other measurements from special field campaigns	9.6%
12. Transportation plans and projections	9.6%
13. Personal exposure monitoring data	6.1%
14. Source emissions reports	.9%
15. Source inspection reports	.9%

Table A10. Percentage of responses to the question "for what purpose, if any, are the following technical resources used within your agency?"

Resources	Public Information	Control Strategy Development	Other	Not Used
Satellite measurements of aerosol optical depth (AOD)	27.7%	15.4%	21.5%	35.4%
Satellite measurements of trace gases (NO2, CO, HCHO, O3)	19.6%	19.6%	17.9%	42.9%
Satellite measurements of land-use, vegetation or land-cover	25.0%	25.0%	20.5%	29.5%
Satellite measurements of cloud cover or radiation	32.1%	7.1%	21.4%	39.3%
Satellite observations of smoke plumes	46.3%	16.8%	28.4%	8.4%
Model estimates of North American boundary conditions or North American Background (NAB)	25.5%	36.4%	5.5%	32.7%
NOAA's National Air Quality Forecasting Capability	61.1%	15.6%	14.4%	8.9%
Data or insights from Discover AQ campaigns	16.7%	24.1%	5.6%	53.7%

Table A11. Percentage of respondents who indicated that each issue remains a barrier to use of satellite data by their organization, for respondents who indicated that their agency had some involvement with AQAST and those that did not.

Barriers	Remains a barrier: AQAST Participants	Remains a barrier: Did not Participate in AQAST
1. Available data are not relevant to air quality management	41.3%	23.8%
2. Hard to find out what data are available or potentially useful	50.0%	76.7%
3. Staff lack time or resources to acquire and process data	69.4%	80.0%
4. Staff lack necessary training and expertise to acquire and process data	52.9%	74.3%
5. Format is not readily usesable	46.3%	50.0%
6. Data are too uncertain for applications of interest	79.5%	66.7%
7. Inadequate coverage or frequency	83.3%	73.7%
8. Not clear if data would be accepted for regulatory purposes	60.5%	62.5%
9. Did not know satellite data could be used for air quality	6.3%	20.0%

Table A12. Mean and standard deviation of responses to the request "please rate your agency's experience with AQAST meetings on the following dimensions." 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree. (N = 54)

Outcomes	Mean, 5 point scale	Std. Deviation
1. Meeting provided information useful to my agency	4.23	.743
2. Meeting created awareness of research that is interesting to my agency	4.23	.642
3. Meeting helped staff in my agency identify or access new resources or tools	4.14	.765
4. Meeting led to new collaborations for my agency	3.76	1.113

Table A13. Mean and standard deviation of responses to the request "Please rate your agency's experience working with AQAST researchers on the following dimensions." 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree. (N = 53)

Outcomes	Mean, 5 point scale	Std. Deviation
1. Created awareness of research that is of interest to my agency	3.93	.986
2. Helped staff in my agency access new resources or tools	3.83	1.010
3. Led to new collaborations for my agency	3.66	1.153
4. Pursued research or developed tools that were relevant and useful to my agency	3.60	1.006
5. Helped my agency solve a scientific or technical problem	3.47	1.156
6. Helped my agency solve an air quality management problem	3.36	1.158
7. Pursued research or developed tools based on my input	3.35	.950